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Broadband terahertz and sub-terahertz CMOS modules for imaging and spectroscopy applications

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Abstract

Miniaturized, low cost and easy to use devices able to carry out analysis in the chemical or biomedical domains could extend the use of imaging and spectroscopic techniques, now widely exploited in the professional sector, to applications in the consumer market or in the domain of point-of-care diagnostics. While a number of advanced techniques based on infrared or optical radiation show great potential for use in highly sensitive biosensors, the use of another part of the electromagnetic spectrum, the so called terahertz band (100 GHz – 3 THz), promise the creation of new devices with the capability of carrying out spectroscopy *and* imaging at the same time, even on samples located in an opaque package. In this paper we present our results demonstrating the possibility to create a miniaturized terahertz imaging and spectroscopy system that can be mass produced at low cost using well-known and robust commercial technologies such as CMOS and 3D chip-scale packaging (3D-CSP). The presented device is able to produce and detect a broadband signal from 20 GHz to 280 GHz with a dynamic range of 44 dB at 140 GHz.

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Keywords: Millimetre wave micro-systems; THz radiation; Nonlinear transmission lines; Vivaldi antenna; THz CMOS

1. Introduction

Imaging, spectroscopy and sensing techniques are widely used in the professional field to study or detect different types of samples. Applications are in chemical analysis, biology, industrial quality control, and clinical diagnostics among others. Although extending the use of those techniques to

applications for the consumer and the mass market seems attractive in many cases, the cost and complexity of current instrumentation strongly limits this development. Miniaturized devices that can be mass produced at low-cost and that are still sufficiently reliable and easy to exploit could extend the use of imaging and spectroscopy also to applications for the everyday life. Moreover, although several instruments exploiting different bands of the electromagnetic spectrum are available, not all regions of the spectrum are currently used. New, unexplored regions could greatly enhance analytic capabilities beyond what is possible today. The terahertz (THz) frequency range is defined as the band of the electromagnetic spectrum extending from roughly 0.1 THz to 3 THz, i.e. between the millimeter waves and the infrared range. Radiation in this frequency range, for a long time under-explored, is now generating a steadily increasing interest due to its unique properties. THz waves can penetrate many dielectric and non-polar materials and can be used for thru-the-package imaging. Microwaves are also suitable for this purpose, but the broader bandwidth and higher frequency of THz signals allow much higher lateral and axial resolution. At the same time, many substances have their unique resonance frequencies in the THz band, so in addition to imaging, also spectroscopy – a known technique often based on infrared or visible radiation - is possible. State-of-the-art THz systems are often based on femtosecond lasers and have considerable cost and size not compatible with consumer applications. Recently, though, a number of THz miniaturized and potentially low cost devices based on CMOS integrated circuit technology have been created [1]-[8]. In this paper, the results achieved in the development of a new miniaturized THz imaging and spectroscopy device are described. The discussed device is built using commercially available and well proved technologies such as CMOS and 3D-CSP. It has a reduced size and can be mass produced at low cost. Transmission or reflection measurement configurations can be both used and size is compatible with the integration of the device into, for instance, a smartphone.

Nomenclature

3D-CSP	3D chip-scale packaging
CMOS	Complementary metal–oxide–semiconductor
TX/RX	Transmitter/Receiver
IF	Intermediate frequency
NLTL	Nonlinear transmission line

2. Implementation of the THz imaging and spectroscopy device

The implemented hybrid terahertz and sub-terahertz device described in this paper is composed of a transmitting (TX) and a receiving (RX) module. Each module has a CMOS chip containing all the analog electronic circuitry required to generate or detect the high frequency signals. To properly transmit or receive the signals an off-chip broadband Vivaldi antenna is used. Chip and antenna are packaged and connected together exploiting a commercial packaging process based on 3D CSP technology. A drawing of the complete terahertz system is shown in Fig. 1, where the RX, located at the left of the figure, and the TX are positioned in a transmission configuration. An *in vitro* study of tissues and other substances, including in liquid form thanks to a flow chamber, is possible. Since TX and RX are independent modules, a reflection configuration can also be implemented. In this case, the object under test can be of different types, including an *in-vivo* sample, such as a patient's skin portion.

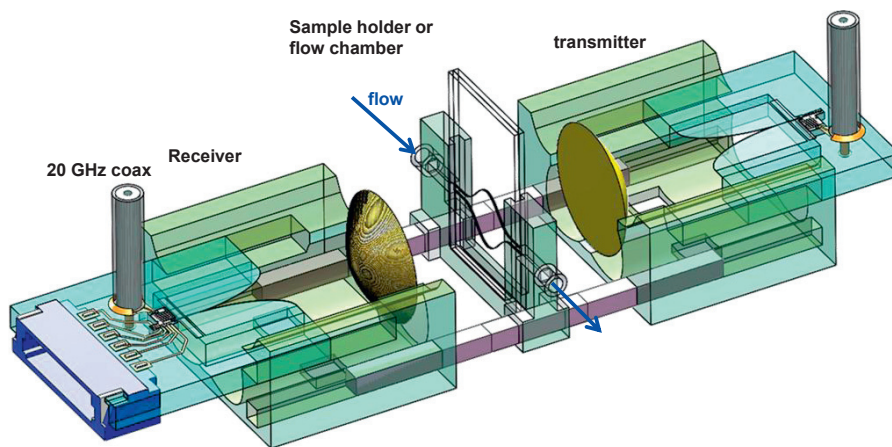


Fig. 1 Hybrid terahertz and sub-terahertz CMOS imaging and spectroscopy device.

A picture of the fabricated device is shown Fig. 2. On the left-hand side of the figure, the transmitter is visible. A miniaturized coaxial cable used to guide input signals from few GHz up to 20 GHz is directly connected to the CMOS chip (only partially visible in the figure due to its small size). On the chip, the signal is multiplied in frequency using a nonlinear transmission line (NLTL), i.e. a transmission line composed by a modified grounded coplanar waveguide periodically loaded with RF MOS varactors type n⁺-poly/n-well [1], [2]. The input signal propagating along the NLTL is progressively reshaped with its falling edge transformed into a fast transition containing multiple harmonics of the input signal up to, at least, 280 GHz. At the output of the NLTL on chip, a connection to the off-chip Vivaldi antenna is created using 3D CSP technology. The choice of such an off chip antenna was due to its compact size, broad impedance bandwidth and high directivity. Implementing the antenna in the package and not on chip allows reducing silicon area and, generally, cost. Also in terms of performance, the off-chip solution has shown better results than the on chip version [9]. In the transmission configuration shown in Fig. 2, the broadband signal emitted by the Vivaldi antenna propagates towards the sample holder. The transmitted signal after the sample propagates towards the receiver located at the right-hand side of Fig. 2. A focusing lens is placed in front of the RX and TX Vivaldi antennas to improve the sensitivity at high frequency. The received signal propagates from the antenna to the chip via a connection very similar to that one present in the transmitter [9].

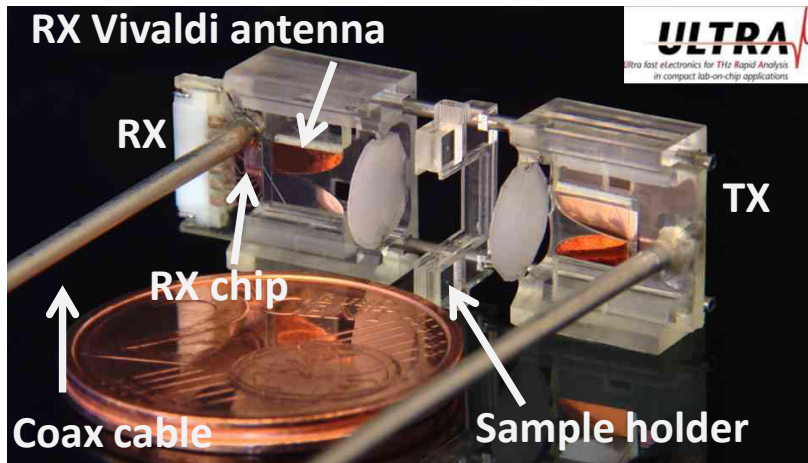


Fig. 2 Photograph of the hybrid terahertz and sub-terahertz imaging and spectroscopy device.

In the receiver's chip, an NLTL and a sampling bridge down-convert the broad band signal containing harmonics from 20 GHz to 280 GHz to a signal with harmonics from 1.2 MHz to 16.8 MHz. The NLTL-based coherent receiver concept [1] has demonstrated functionality up to 480 GHz and above [1][10]. Being on the same chip of the NLTL, the sampling bridge composed by Schottky diodes is also implemented in 65 nm CMOS process. While Gallium Arsenide Schottky diodes are rather common and capable of achieving cut-off frequencies higher than 100 GHz, CMOS silicon Schottky diodes have been implemented rarely [11][12]. To reduce Schottky diodes parasitics and achieve a high cut-off frequency of 430 GHz, in this work a special Schottky diode layout has been devised [12], but no particular process changes have been used to guarantee perfect compatibility with standard commercial 65 nm CMOS and hence simplify production.

3. Device evaluation

To test the developed terahertz device, the transmitter and receiver are mounted in a measurement test-bench on two plastic supports, see Fig. 3. In the experiment discussed here, the transmitter located on the left of the figure is fed with a 20 GHz sinusoidal input signal via a coaxial cable. Harmonics of this signal are generated by the transmitter and emitted into free space by the antenna. In this transmission configuration, the emitted terahertz beam impinges on a sample (not shown in the figure) and the transmitted part of it is detected by the receiver located on the right-hand side of Fig. 3. The receiver is fed with a signal with frequency $20\text{GHz} + 1.2\text{MHz}$ and the harmonics of this signal are used to down-convert the frequency components of the received signal via mixing in the sampling bridge of the RX. The intermediate frequency (IF) signal contains fourteen measurable harmonics in the range 1.2 MHz to 16.8 MHz so that measurements at IF can be carried out with low frequency electronics. To visualize directly the down converted spectrum of the received signal, an Agilent spectrum analyzer is used in this work. In Fig. 4, the measured power spectrum of the received signal is shown in the cases of 1 cm and 5 cm distance between TX and RX. The received power decreases when distance increases due to the imperfect collimation of the broadband terahertz beam. In this device characterization test, no sample is located between transmitter and receiver, so the features present in the spectrum are intrinsic to the

overall terahertz system and should be calibrated out when a sample is measured. A simple way to do it is to divide the power received at any frequency obtained when the sample is analyzed by the power received when no sample is present.

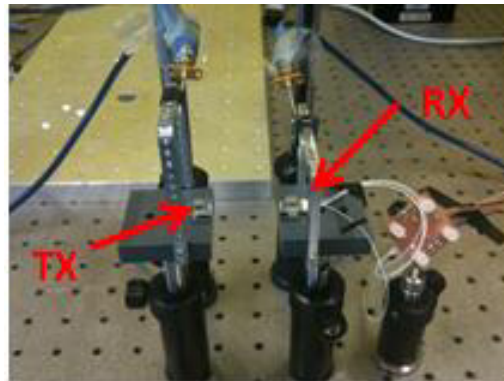


Fig. 3 Photograph of the measurement test bench of the THz microsystem. Both transmitter (left) and receiver are located on two plastic supports. A printed circuit board (left) is used to interface the connections from the device's package with the measurement instruments.

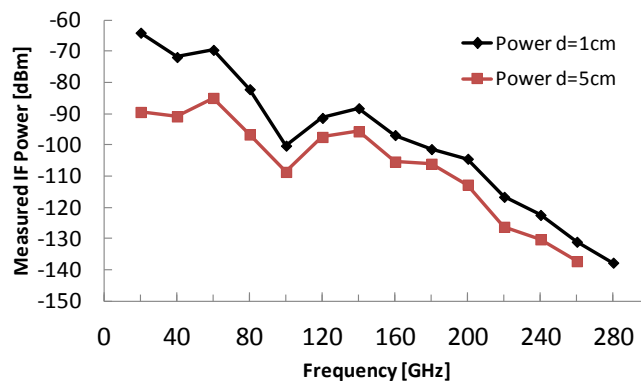


Fig. 4 Measured IF power spectrum of the detected signal using the terahertz micro system.

The dynamic range of the system, calculated as the ratio of the power received when free propagation of 1 cm is allowed and the noise detected when the signal is blocked with a metal plate is shown in Fig. 5. From the figure it is possible to determine that the maximum available dynamic range is 44 dB at 140 GHz whereas at 260 and 280 GHz only 7 dB and 8 dB respectively are available. At 300 GHz the signal cannot be distinguished from the noise floor of the system. Low dynamic range at high frequency is due to the low available signal power. In the lower part of the measured band instead, the low dynamic range is related to high noise levels. To understand this, it should be considered that at low frequency, due to the longer wavelengths, a larger part of the transmitted signal doesn't travel through the sample, but instead it reaches the receiver via multiple reflections, contributing to the increase of the noise.

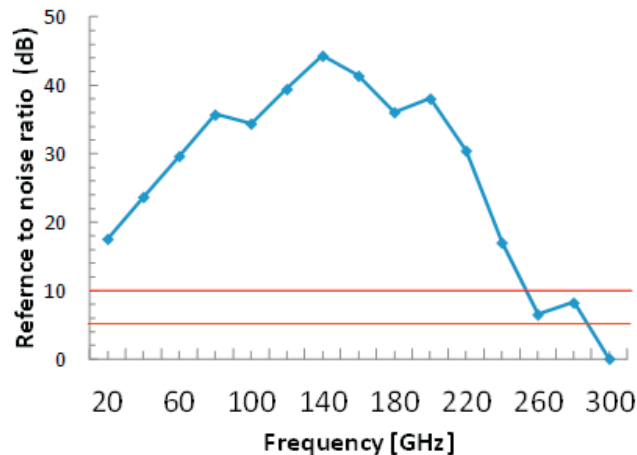


Fig. 5 Dynamic range of the terahertz microsystem.

4. Conclusion

This paper demonstrates a complete terahertz micro system suitable for imaging and spectroscopy applications. The device is composed of a transmitting and a receiving module. A silicon integrated circuit fabricated in a commercial 65 nm CMOS technology is packaged with an off-chip Vivaldi antenna using a commercial 3D-CSP technology. The system has demonstrated functionality in a broadband range extending from 20 GHz to 280 GHz. The maximum achieved dynamic range is 44 dB at 140 GHz. The harmonics generated and detected can be used for imaging at several frequencies or to carry out spectroscopy of different materials. Compared with current state-of-the-art terahertz technology based on electro-optics, the results achieved demonstrate the possibility to build miniaturized terahertz modules that can be mass produced at low cost using well proved and robust commercial technologies such as CMOS and 3D-CSP.

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